Response to Reviewer Comments: **Climate and Cryosphere Cause Water Yield Regime Shifts in the Upper Brahmaputra River basin**

Reviewer 1

Comment 1.1: Li et al. provide a case study to study the influence of climate and cryosphere on the water yield in the Brahmaputra. To do this they collected a long time series for climatic and precipitation data and analyzed it to find the water yield has changed over the time period studied. They find that there are substantial changes and attribute this mainly to the combined effect of climate and cryosphere. I think this study has value (I especially like the introduction) and should be considered for publication. However, I have several issues that I think should be addressed.

Reply: We are grateful for Dr. Florian Ulrich Jehn's thoughtful evaluation and support of our work. We will reply to all comments in detail in the following, highlighting changes in the revised manuscript. **We aim to clarify the reasons for selections of climate and vegetation indices, and double mass curve (DMC) in this study**, which will improve the quality of the revised version.

General Comments

Comment 1.2: First, the study does not provide enough information about its data. For example, after reading the study I am still unsure what exactly is meant when the study talks about climate being a major factor in its analysis. Is it the mean temperature? Is it some indices? Is it something completely different? Same goes for the term cryosphere, which is used quite loosely.

Reply: We thank the reviewer for pointing this out. We now clearly define the variable that we consider as a proxy for the effect of climate on water yield.

Based on water balance ($P = R + AET + \Delta S$), the net effect of climate on regional water yield is expressed in both precipitation (P) and actual evaporation (AET). Hence, we use effective precipitation (eP, P - AET) to assess climate contributions to hydrological changes in the double mass curve (DMC) analysis carried out in this study. Therefore, we consider eP as a proxy to climate, supported by Wei and Zhang (2010) and Zhang et al. (2019). In the revised version, we clearly explain the reasons for selecting eP as a proxy for climate effects as follows:

Line 109–111: The selection of climate and vegetation indices used in the DMC technique is an important issue. Previous studies haves shown that effective precipitation (eP, P-AET) can reflect more information of climate on WY compared with individual P or AET, and be regarded as a reliable proxy to climate (Wei and Zhang, 2010; Zhang et al., 2019).

Cryospheric contributions to water yield calculated by the DMC method mean that, melt waters released from **glacier and snow melting with warming** contribute to river flow. In DMC, we define cryospheric contributions to water yield as the values of total water yield deviation minus the sums of climate and vegetation contributions. Related revisions are shown as follows:

Line 116–118: To obtain cryospheric contribution to WY, we firstly build two types of DMC plots (see Figure S2) to assess the contribution of climate (eP) and vegetation (LAI), and then subtract the sum of estimated contributions from total WY deviations (results are shown in Figure 2). The calculation process of the DMC is shown as follows:

Comment 1.3: Second, after reading the methods it is not clear to me how the study is able to differentiate between the influence on climate, cryosphere and vegetation. This section would profit from a more in depth explanation. In addition, why using this method? Why do you think it is especially good for your kind of study?

Reply: We thank the reviewer for this suggestion.

For a large natural mountainous watershed, it still remains not clear about the hydrological responses to climate change and associated environmental changes, e.g. vegetation and cryosphere. That leads to great uncertainties when assessing water yield changes using hydrological models. While, long-term annual runoff observations and high-resolution precipitation records in the UBR basin provide a good opportunity for statistical models to investigate hydrological responses to climate warming.

The Double Mass Curve – a data-driven statistical model – has been widely been applied to estimate water yield responses to environmental changes in the hydrological community. We assume that in the UBR basin, water yield is affected by climate (e.g. precipitation and evaporation), vegetation greening or browning, and cryospheric loss (e.g. glacier and snow melting). Hence, we can estimate cryospheric contributions to water yield by subtracting the sum of contributions from climate and vegetation from total deviations using the DMC method.

We now clearly explain the reasons for using the DMC to separate climate, vegetation and cryosphere contributions to water yield in the manuscript. Related changes in Introduction and Methods section are shown as follows:

Revisions in Introduction:

Line 47–51: Lastly, the present inadequate understanding of hydrological responses to complex interactions among climate, vegetation, and cryosphere limits the application of hydrological models in those glacier-fed watersheds (Pellicciotti et al., 2012). While, long-term observed runoff data and recent high-resolution precipitation records may give a pathway for using statistical methods to estimate runoff responses to warming in mountainous regions.

Revisions in methods:

Line 101–108: The DMC used here is a plot of the cumulative data of one variable versus the cumulative data of another related variable in a concurrent period. It has previously been used to assess the individual effect of climate (Gao et al., 2011), forest disturbance (Wei and Zhang, 2010), wildfire (Hallema et al., 2018), and cryosphere (Brahney et al., 2017) on water resources. For the large and pristine UBR and other mountainous basins, climate, vegetation, and cryosphere play important roles in hydrology, and these three parts must be together considered to accurately estimate hydrological responses to warming. It is considerably hard to directly calculate the supply of melt waters to WY due to the lack of glacier monitoring, while long-term runoff observations and high-resolution climate and vegetation data make it possible to use the DMC technique, a data-driven statistical method, to estimate cryospheric contribution to WY.

Comment 1.4: Third, the study finds a turning point for the behavior of the river. This seems quite important to me, but is never really discussed. Why did this change happen? What consequences will it have?

Reply: We thank the reviewer for pointing this out. The turning point is identified by the Pettitt method and used to split the entire period into two parts in which water yield shows substantial changes in both the magnitude and direction (Section 3.2). In fact, this is a prerequisite step for using the DMC method to assess the relative importance of climate, vegetation and cryosphere in driving hydrological changes between the two periods (see Methods).

As revealed in our study, significant water yield changes in two periods are determined by the turning points, in which climate and cryosphere both contribute to magnitude increases in water yield, but climate, represented by $P - AET$, is more important for the trend changes in water yield. Further, We make related analysis and discussions to stress the dominant role of precipitation in water yield changes in the revised version as follows:

Revisions in Results:

Line 185–190: Results in Figure 6 show that, although the correlation varies greatly across basins ranging from 0.11 to 0.93 after the TP, climate typically is positively associated with total WY, in which the correlation is significant in half of basins ($p < 0.05$), again revealing the major role of climate in the hydrological trends in the entire UBR basin. Further analysis shows that, precipitation is much more important, because it exhibits the stronger reverse in trend compared with that in actual evaporation (Figure S5), which is also similar with direction changes in WY (Figure 4b).

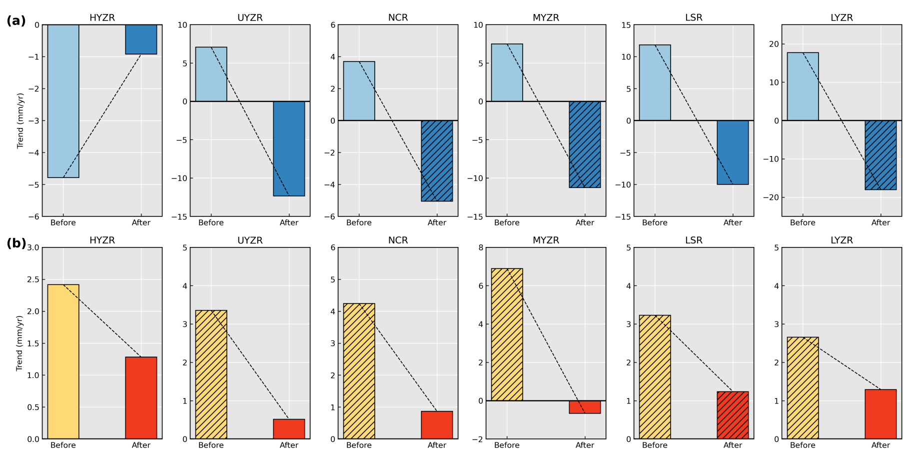

Figure S5. Direction of precipitation (a) and actual evaporation (b) changes. The black hatching represents the statistically significant trend ($p < 0.05$). The color of boxes represents the period before (light color) and after (dark color) the turning point (TP).

Revisions in Discussion:

Line 215–218: However, climate, especially precipitation, remains the most important factor controlling the declining WY trend after the TP in most regions (Figure 6 and S5), and may lead to occurrence of turning points (Figure 3c+d), which is in agreement with previous studies (Li et al., 2021; Wang et al., 2021). This suggests the importance of precipitation and its projections on future hydrological process in mountainous watersheds (Lutz et al., 2014).

Specific Comments

Comment 1.5: The study states several times that the increase meltwater has the potential to alleviate the loss of water availability. I also think this is the case, but it should be made clearer that this will only be a temporary relief until the glaciers have melted.

Reply: We agree with the reviewer that meltwater is only a temporary relief. We will improve these statements. As mentioned, there may be a "maximum cryospheric contribution to water yield" ('peak water' Gleick and Palaniappan (2010)). Glacier runoff will increase with warming and compensate for low flow during droughts (see negative correlations with decrease runoff in most basins, Figure 6), while steadily decrease after reaching "peak water" due to the reduced glaciers and snow (see the positive correlation in the HYZR basin, Figure 6a).

In the revised manuscript, we try to link our results with "peak water". For example,

Revisions in Results:

Line 193–201: In contrast to positive contributions of climate, we find that WY caused by cryosphere exhibits a negative association with reduced total WY in recent years in the UYZR ($r = -0.39$, $p > 0.05$) and LSR ($r = -0.36$, $p > 0.05$) basins. The negative but weak relationship indicates that melt waters from cryospheric loss may compensate for low flow, and even mitigate water shortage risks, as suggested by Bibi et al. (2018) and Gleick and Palaniappan (2010). Also, the compensating effect from cryosphere is much stronger in the MYZR ($r = 0.47$, $p > 0.05$), and together with climate contributions, contributes to the increasing WY trend (Figure 4). Different from other regions, however, the HYZR basin shows a significantly positive relationship between cryospheric contributions and total WY ($r = 0.76$, $p < 0.05$), indicating that cryosphere instead of climate leads to the downward trend in headwaters. This signifies that in this region, cryospheric contributions have already passed a maximum supplying to river flow, due to decreased glaciers and snow under continuous warming, which is in agreement with Huss and Hock (2018).

Line 202–206: We further analyze the relationship of cryospheric contributions to total WY (RC_s) with temperature (Figure S6). In the HYZR basin, WY resulting from cryosphere continues to increase with temperature until a maximum is reached, beyond which cryospheric contribution to total WY begins to decrease. In addition, the compensating effect of melt waters also can be seen clearly in the UYZR, MYZR and LSR basins; WY caused by cryospheric loss keeps a positive relationship with the increase of temperature, further supporting the higher correlation in these basins (Figure 6).

Revisions in Disucssion:

Line 228–234: Also, cryospheric contribution to mountainous hydrology is important – melt waters from glaciers and snow melting can alleviate water resources deficits, mainly caused by decreased precipitation in recent years (Figure 6). This finding is also supported by observed glacier runoff data (Yao et al., 2010) and several modeling studies (Lutz et al., 2014; Zhang et al., 2020; Wang et al., 2021). However, after glacier runoff reaches a maximum, defined as 'peak water' (Gleick and Palaniappan, 2010), cryospheric mass loss cannot sustain the rising meltwaters with atmospheric warming (e.g. the HYZR basin in the study). The decreased glacier areas and associated hydrological changes will substantially affect water resources management.

Comment 1.6: What are the specific reasons that vegetation was studied? Are the any reasons to assume that the vegetation has changed significantly in the time period?

Reply: Many studies have indicated that vegetation will significantly change water yield based on the statistical or physical models. Also, recent study by Li et al. (2021) revealed that vegetation greening in this region may redistribute water resources through time. Therefore, we use the DMC in the study to estimate vegetation effects on water yield.

Comment 1.7: Figure S2 belongs in the paper in my opinion, as it seems like this is your main plot, which all following plots refer to.

Reply: We thank the reviewer for this suggestion with which we agree. We have placed it in main text.

Comment 1.8: Figure 1: Please change this 3D pie chart to bar char, as those are much easier to read.

Reply: Thank you for pointing it out.

Comment 1.9: Do the abbreviations that are used to label the subcatchments have any meaning?

Reply: Yes. For example, "HYZR" means the headwater watershed in the Yarlung Zangbo River (YZR) basin, and "LSR" means Lasha River basin. We create a table to summarize the information in main text.

Line 70–71:

Table 1: Information of six sub-basins divided by the locations of hydrological stations. The column "Abbre." and "Full" mean the abbreviations and full names of sub-basins. The column "River" indicates whether the basin is located in the main or branch river of the Yarlung Zangbo River (YZR). The column "Station", "Lon.", and "Lat." indicate names and geolocations of hydrological stations. The column "Area" means the total area of sub-basins. The column "TP" indicates the turning point using the Pettitt method, in which a significant tuning point is labeled with *.

Abbrev.	Full name	River	Station	Lon. (°)	Lat. (°)	Area (km^2)	TP
HYZR	Headstream	main	Lhatse	87.57	29.12	49,739	1995
UYZR	Upstream	main	Nugesha	89.71	29.32	43,916	1998*
NCR	Nianchu River	branch	Shigatse	88.89	29.28	14,359	1997*
MYZR	Midstream	main	Yangcun	91.82	29.26	20,004	1997*
LSR	Lhasa River	branch	Lhasa	91.15	29.64	25,601	1996
LYZR	Downstream	main	Nuxia	94.65	29.46	45,017	1997

Comment 1.10: Did you check if you evapotransporiration is roughly correct? You used evapotransporation data from a global model, which might have not been calibrated well to regions such extreme as yours.

Reply: We thank the reviewer for pointing this out. As we do not have access to observed actual evaporation data in this region, we used AET from GLEAM. This dataset has been extensively validated across varied vegetation types in China and has shown good performance with in situ observations.

Related revisions are as follows:

Line 85–87: Regional actual evaporation (AET) is acquired from Global Land Evaporation Amsterdam Model (GLEAM) (Martens et al., 2017). The evaporation product has been validated in different biome types in China and has shown high correlations with in-situ eddy covariance AET (Yang et al., 2017).

Comment 1.11: Why did you choose LAI as a proxy for vegetation and not some other measure?

Reply: Thanks for your questions about the selections of vegetation indices. We give the reasons in the revised version.

Line 111–115: LAI quantifies the amount of leaf area in an ecosystem and becomes an important variable reflecting vegetation structures and biophysical processes (Fang et al., 2019; Forzieri et al., 2020), and Li et al. (2021) has used LAI to investigate vegetation effects on seasonal hydrology in the UBR basin. Hence, we consider eP and LAI as the indices of climate and vegetation respectively, and use their time series as the inputs in the DMC model.

Comment 1.12: Have you considered also checking for the runoff-ratio? This seems like a variable that should give you some additional information.

Reply: We thank the reviewer for this suggestion. As effective precipitation is one of the main explanatory variable considered in this study, we decided to use just water yield, or runoff depth as the target variable. This allows us to robustly apply the statistical method (DMC) to quantify hydrological responses to climate warming.

Comment 1.13: Please change Fig. 3 and Fig 4. to boxplots or swarmplots (depending on your sample size you calculated your mean and standard deviation from). Having just a bar plot with a standard deviation does not really show how your underlying data looks like.

Reply: We agree with the reviewer. We will use boxplots to support our analysis. Note the labelled numbers have been changed.

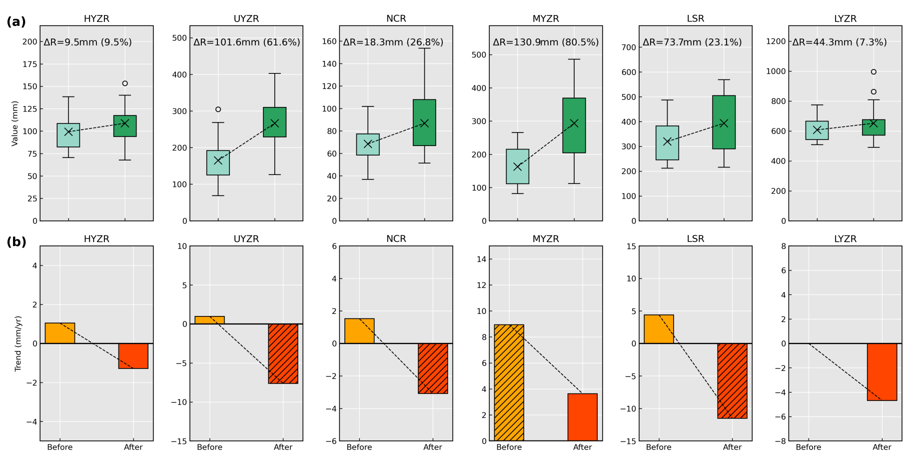

Figure 4. Water yield regime shifts in the entire UBR basin. (a) Magnitude of water yield changes. Black "x" signals show the mean of water yield in each boxplot. (b) Direction of water yield changes. The black hatching represents the statistically significant trend ($p < 0.05$). The color of boxes represents the period before (light color) and after (dark color) the turning point (TP).

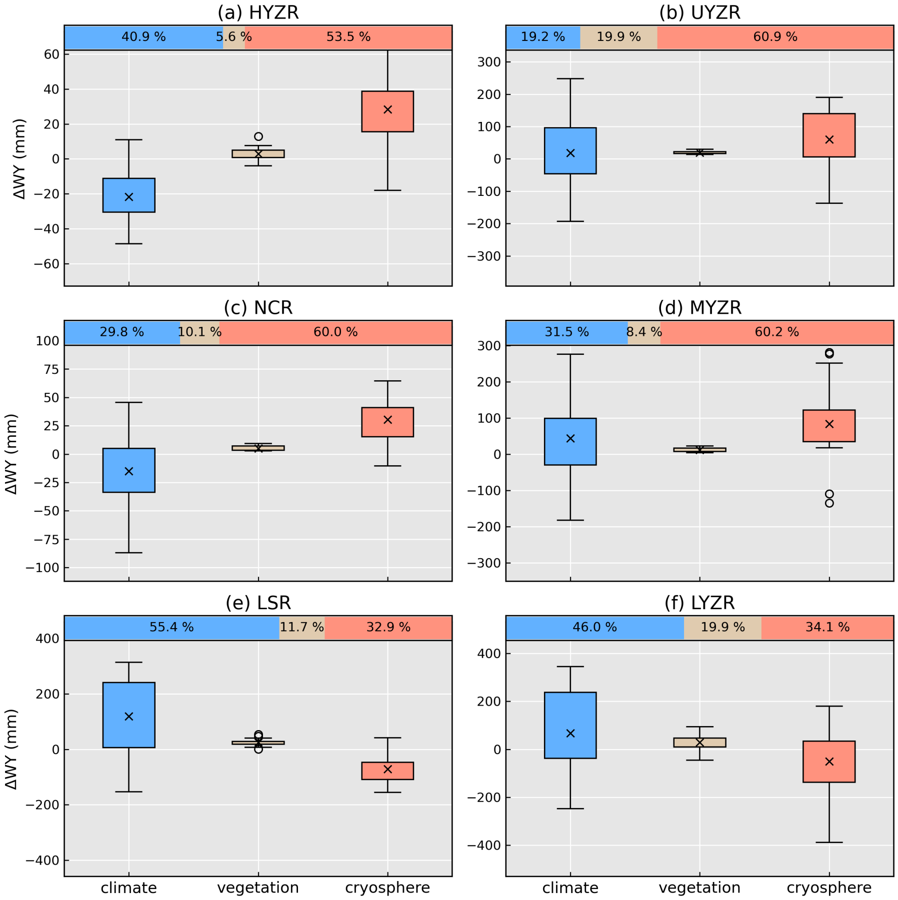

Figure 5. Attribution analysis of magnitude increases in water yield due to climate (ΔWY_c, blue box), vegetation (ΔWY_v, tan box), and cryosphere (ΔWY_s, red box), and their relative contributions (the bar with colors on the top) in each basin. Black "x" signals show the mean of water yield deviations (see Figure 2) in each boxplot.

Comment 1.14: Are your p-values corrected? If not, this would mean that likely in Figure 5 there are way fewer significant trends.

Reply: Thanks for your comments. The p value here is correct, but I am sorry that the labelled n is wrong due to a minor programming error. In the revised version, we have corrected this error, and will only show the regression lines in Figure 6 when p value is less than 0.05, and use "significant" or "significantly" in main text. Related revisions in the manuscript are as follows:

Line 185–192: Pearson's correlation coefficient is applied to determine the role of climate, vegetation, and cryosphere in the reversed or slowed WY trend after the TP, as shown in Figure 4b. Results in Figure 6 show that, although the correlation varies greatly across basins ranging from 0.11 to 0.93 after the TP, climate typically is positively associated with total WY, in which the correlation is significant in half of basins ($p < 0.05$), again revealing the major role of climate in the hydrological trends in the entire UBR basin. Further analysis shows that, precipitation is much more important, because it exhibits the stronger reverse in trend compared with that in actual evaporation (Figure S5), which is also similar with direction changes in WY (Figure 4b). Additionally, despite the weak contribution of vegetation (Figure 5), its positive role in WY changes is more apparent in the drier

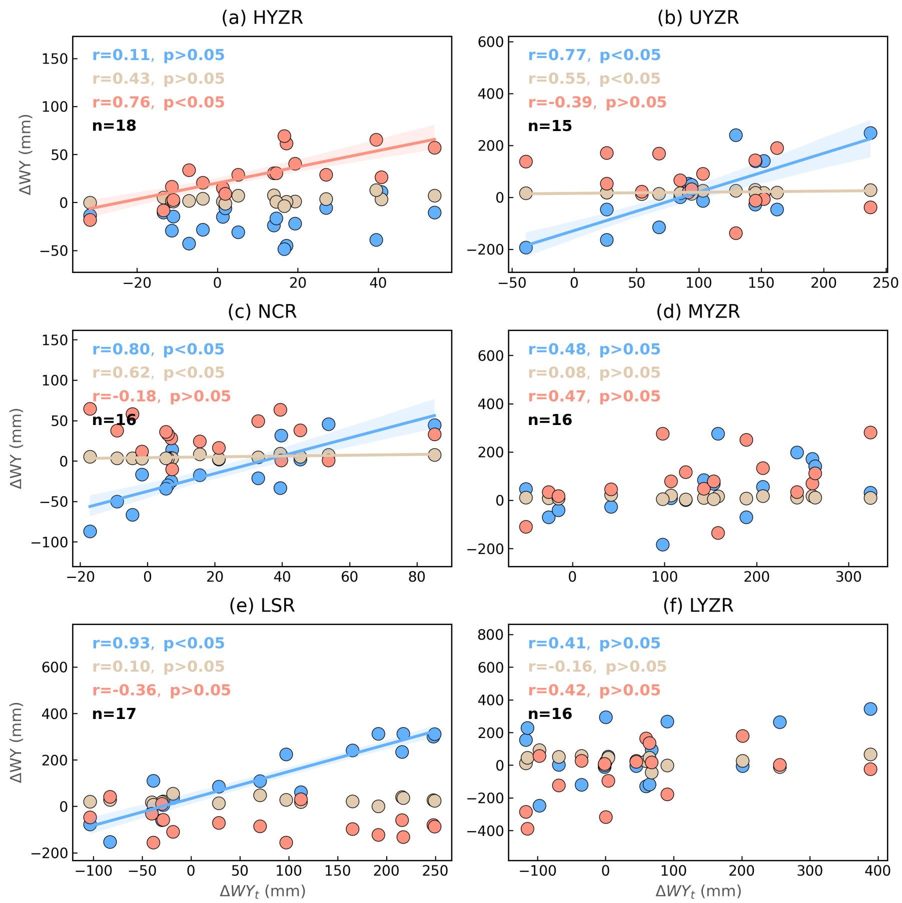

Figure 6. The relationship between time series of total water yield deviation ($\Delta WY_t(t)$, x-axis) and its components (y-axis) induced by climate ($\Delta WY_c(t)$, blue point), vegetation ($\Delta WY_v(t)$, tan point), and cryosphere ($\Delta WY_s(t)$, red point), respectively. The fitting line and its 95% confidence interval are shown only when p value < 0.05. n indicates the number of years after the TP, which is determined by the Pettitt method (See Table 1 and Figure 3c).

basins (such as UYZR, and NCR), while the correlation is negative in the relatively humid LYZR basin.

Line 193–201: In contrast to positive contributions of climate, we find that WY caused by cryosphere exhibits a negative association with reduced total WY in recent years in the UYZR (r = -0.39, p $>$ 0.05) and LSR (r = -0.36, p $>$ 0.05) basins. The negative but weak relationship indicates that melt waters from cryospheric loss may compensate for low flow, and even mitigate water shortage risks, as suggested by Bibi et al. (2018) and Gleick and Palaniappan (2010). Also, the compensating effect from cryosphere is much stronger in the MYZR (r = 0.47, p $>$ 0.05), and together with climate contributions, contributes to the increasing WY trend (Figure 4). Different from other regions, however, the HYZR basin shows a significantly positive relationship between cryospheric contributions and total WY (r = 0.76, p $<$ 0.05), indicating that cryosphere instead of climate leads to the downward trend in headwaters. This signifies that in this region, cryospheric contributions have already passed a maximum supplying to river flow, due to decreased glaciers and snow under continuous warming, which is in agreement with Huss and Hock (2018).

Comment 1.15: The text is quite heavy on abbreviations, which makes it harder to read. Please consider just writing the words out instead of abbreviating them.

Reply: Thank you for the suggestions. We have deleted some abbreviations in main text, such as "Third Pole (TP)". And we also will provide a table (see Table 1 in main text) to indicate some abbreviations clearly.

Technical corrections

Comment 1.16: L19-21: I am not able to parse this sentence.

Reply: We thank the reviewer for pointing this out. We have rewritten the abstract and convey the main information clearer to readers.

Line 1–15: Although evidence of hydrological responses to climate is abundant, the reliable assessments of water yield (WY) in mountainous watersheds remain unclear due to intensified cryospheric changes. Here we examine long-term WY changes during 1982–2013 in the Upper Brahmaputra River (UBR) basin on the basis of annual runoff observations. Results show that hydrological regime shifts have occurred in the late 1990s; magnitude increases in WY range from ∼10% to ∼80%, while the directions of WY changes reverse from upward to downward after the late 1990s. We then use the double mass curve (DMC) technique to assess the effects of climate, vegetation, and cryosphere on WY regime shifts. Results show that climate and cryosphere together contribute to over 80% of magnitude increases of WY in the entire UBR basin, in which the role of vegetation is nearly negligible. The combined effects, however, are either offsetting or additive, leading to slight or substantial magnitude increases, respectively. Climate change, particularly precipitation decline leads to the downward WY trend in recent years, while melt waters from cryospheric changes may alleviate water shortage in some watersheds. In headwaters, however, cryospheric contributions to WY have declined due to reduced glaciers and snow under warming. Therefore, the combined effects of climate and cryosphere on WY should be considered in water resources management in mountainous watersheds, particularly involving co-benefits for upstream and downstream regions.

Comment 1.17: L45: would delete this mention of "Third Pole" as this exact phrasing has already been used in the paragraph above it.

Reply: Yes. It is not important for this study, and we have deleted it.

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